# ENERGY CROP EVALUATION BY LINEAR PROGRAMMING

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#### ABSTRACT

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It is demonstrated how mathematical modelling can be used to evaluate energy crops and to determine optimal production scenarios. A generalized linear programming model is presented which can be used to optimize agricultural production systems by evaluating the time-varying competition between crops for land, labor and machinery. The linear programming model uses a multi-stage structure to force activities such as land preparation, planting and harvesting to occur in the proper sequence.

In addition, crop yield reductions for untimely field operations are considered. The model schedules activities and determines the amounts of each crop which maximize profits according to price, time and resource constraints. Also, shadow prices are given for each scarce resource. Shadow prices represent the value of an additional unit of a resource. Shadow prices are effective in identifying critical constraints (i.e. bottlenecks) at various production stages. A case study, based on actual field data, is included to provide an illustration of the analysis procedure.

## INTRODUCTION

Production of energy from biomass is a small, but growing part of the U.S. energy industry today. The use of wood for heat has increased significantly and the use of corn (maize) grain for ethanol as an octane booster for gasoline has steadily increased. Mr. James Stearns, Director of Alcohol Fuels,

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U.S. Department of Energy, estimated an annual ethanol production capacity in the U.S. of 568 million l in 1981 (Hartnett, 1981), and Scheller (1983) recently estimated total fuel ethanol production at 872 million l in 1982 with significant new capacity under construction. Crops such as sugar beets, sweet sorghum and potatoes have the potential to yield more ethanol per ha than does corn. Many new plant species are being tested to determine their potential as energy producers.

Many crops are being evaluated on their energy output per ha; however, other criteria should also be considered. For example, questions arise about the production system dynamics and economics of producing energy crops:

How critical are the timings of planting, harvesting and other operations? Crop returns are very sensitive to optimal timing. Research with corn has shown that yields are reduced by late planting, and that harvesting losses are directly related to timing because of the weather effects.

Does the energy crop compete with conventional crops for labor and machinery?

Can the energy crop be produced with the same machinery the producer uses for other crops?

Is it feasible to store the energy crop or should it be sold directly?

What commodity price relationships are required for energy crops to become profitable? It is not enough to simply compute the average return per ha for a particular energy crop and compare that with the return for a conventional crop because this ignores the dynamics of the agricultural production system.

System dynamics have been shown to be very important in crop agriculture because of the practical importance of timeliness. Morey et al. (1971) and Castain et al. (1982) used weather-based simulation to show the importance of balancing the capacities of the harvesting and drying equipment for corn grain. They also showed quantitatively that a certain amount of machinery overcapacity is less costly than an equivalent amount of undercapacity. Weather effects are often non-linear; that is, a 'bad' season reduces profits much more than a 'good' season increases them. Also, interactions within the production system are very important. Maurya et al. (1981) used simulation to show how cornstalk harvesting, an added operation between corn grain harvest and fall tillage, could reduce yields the following year because of the cumulative delay.

The first practical energy crops will be multi-use crops such as corn and sunflowers, where ethanol or oil may be produced or the grain sold for conventional non-energy uses (Bagby et al., 1980). As processing plants are built and markets develop exclusively for energy crops, then producers will experiment and grow these crops if they are economically feasible. The effects of energy prices in relation to food and feed prices will be important in determining the economic feasibility of biomass energy. Economic feasibility should be addressed now, before large research investments are made without regard to agricultural dynamics. Barring major disruptions of our conven-

tional petroleum sources, farmers must respond to economic forces rather than to futuristic concerns about dwindling non-renewable resources.

#### **OBJECTIVE**

The objective of this work was to demonstrate an analysis procedure for evaluating the producion potential of energy crops by considering the effects of: (1) weather; (2) time-varying competition between crops for land, labor and machinery; and (3) various processing and marketing strategies.

## PROCEDURE

In order to realistically assess the production potential of energy crops, the systems analysis procedure should include crop input/output data, growth and development relationships, and the timed competition for limited farm resources. A linear program was used which has been developed to help agricultural producers determine crop mixes that maximize profits. We have entered data for a potential energy crop into a data set for a conventional farm management program. By changing the price, yield and/or cost coefficients for this energy crop, we can determine at what price producers could economically afford to adopt a particular energy crop in competition with conventional crops. This gives an indication of which crops need to be researched and developed to create profitable energy crop alternatives for conventional production systems.

The linear programming (LP) model used was the Purdue Crop Budget Model B-10 (also referred to as REPFARM) (McCarl, 1982, McCarl and Pheasant, 1983). To run Model B-10, one must first specify time periods during the crop year. Up to 26 time periods of variable lengths may be used. Within each of these major activity periods, the number of good field days and resource allotments, such as labor and machinery, are specified as well as necessary field operations. For example, a typical calendar of events is shown in Table I. The only field operation allowed in Period 1 is seedbed preparation, whereas seedbed preparation and corn planting can compete for resources in Period 2, but of course planting cannot precede seedbed preparation. After the time and other resource constraints and equipment operations have been specified, data are entered for each crop. Crop data include variable production costs, timed resource demands, yield response and final crop moisture contents for each possible combination of planting and harvesting periods. In addition, processing and storage options are specified with corresponding market prices.

The results are presented by a report generator that prepares crop budgets, activity reports, resource utilization reports and a profit summary (before or after taxes). Also, shadow prices are given for each scarce resource, and they show bottlenecks at various operation stages. For example, a high shadow price for field hours at planting time suggests that a larger planter or more hours to operate the planter may substantially increase profits.

TABLE I Calendar of acceptable dates of operations

Period	Date		rn			So	ybea	ın		Sw	eet s	sorgh	um	Wheat			Double crop soybean				
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	$4^{\mathbf{a}}$
1	6 December — 18 April	X			******************************	X		************		X								<del></del>	***************************************	**************************************	
2	19 April — 25 April	X	X			X				X											
3	26 April – 2 May	X	X			X				X											
4	3 May — 9 May	Χ	Χ			X	Χ			X	X										
5	10 May — 16 May	Χ	X			X	X			X	X										
6	17 May — 23 May	Χ	X			X	X			X	X										
7	24 May — 30 May	X	Χ			X	X			X	X										
8	31 May — 6 June	Χ	Χ			X	X			X	X										
9	7 June — 13 June					X	Χ			X	X										
10	14 June — 20 June					X	X			X	X										
11	21  June - 27  June															X			X		
12	28 June — 4 July															X			X		
13	5 July - 11 July															X			X		
14	12 July - 29 August											X	X			X					
15	30 August — 12 September											X	X								
16	13 September – 26 September											X	X								
17	27  September - 10  October			X	Χ			X	X			X	X		X						
18	11 October — 31 October			Χ	Χ			Χ	X			X	X		Χ					X	
19	1  November = 21  November			Х	X			Χ	X				X		X					X	
20	22 November — 5 December			Х	Χ			Х	Χ				Χ							X	

<sup>a1, seedbed preparation and chemical application;
2, plant;
3, harvest;</sup> 

<sup>4,</sup> land preparation (plowing).

In addition to use for crop selection, the model has been used to study equipment sizing and selection (Danok et al., 1980; Krutz et al., 1980). Parsons et al. (1981) evaluated the cost of machinery downtime during planting and harvest periods. Brink and McCarl (1978, 1979) studied risk modelling and have outlined procedures whereby risk aversion can be incorporated into the model.

### CASE STUDY: SWEET SORGHUM

This case study is intended to demonstrate how linear programming can be used to analyze and evaluate the system dynamics of a particular energy crop, sweet sorghum, in competition with conventional crops which are currently being grown in the central portion of Indiana. Sweet sorghum (Sorghum bicolor (L.) Moench) is a leading potential energy crop for integration with conventional crops because of its high yields of fermentable sugars and its adaptability to a wide range of climates and soil types.

Conventional crops currently being grown in central Indiana are corn, soy-beans and winter wheat. Optimal planting dates for corn and soybeans occur in early and late May, respectively. Since the optimal planting dates do not directly coincide, the two crops are said to be complementary with respect to planting. This tends to smooth the demand for labor and machinery during planting, resulting in higher machinery utilization without sacrificing timeliness. Average yields for corn and soybeans are shown in Tables II and III for various planting and harvest dates in Indiana (Doster et al., 1982).

Winter wheat is a crop which is competitive for labor with corn and soybeans during wheat planting periods, but complementary for labor and machinery during the wheat harvest periods. Wheat is planted in October and harvested in the following July. Many farmers also grow short-season varieties of soybeans directly following the mid-summer wheat harvest. This prac-

TABLE II Average corn yield (t/ha) for various planting and harvest dates in Central Indiana

Planting date	Harvest date									
	27 September 10 October	- 11 October 31 October	1 November 21 November	22 November— 5 December						
19 April—25 April	8.436	8.261	7.821	7.382						
26 April— 2 May	8.788	8.612	8.173	7.733						
3 May – 9 May	а	8.612	8.173	7.733						
10 May-16 May	a	8.261	7.821	7.382						
17 May 23 May	a	a	7.294	6.855						
24 May 30 May	a	a	6.415	6.064						
31 May 6 June	a	a	a	4.833						

<sup>&</sup>lt;sup>a</sup>Corn would not normally mature for harvest by the dates shown.

Planting date	Harvest date								
	27 September– 10 October	- 11 October 31 October	1 November— 21 November	22 November— 5 December					
3 May- 9 May	2.953	2.892	2.802	2.682					
10 May-16 May	3.013	2.953	2.892	2,742					
17 May-23 May	3.013	2.953	2.892	2.742					
24 May-30 May	a	2.832	2.772	2.682					
31 May-6 June	a	2.712	2.651	2.561					
7 June-13 June	a	2.561	1.501	1.410					
14 June-20 June	a	2.350	2.290	2.199					

<sup>&</sup>lt;sup>a</sup> Soybeans would not normally mature for harvest by the dates shown.

tice of growing two crops on the same land (during 1 year) is called double-cropping. The wheat/double-crop soybean sequence provides another way to smooth the demand for labor and machinery during critical periods. The timing of operations for the wheat/double-crop soybean mixture is shown in Table I. Average yields for wheat and double-crop soybeans are given in Tables IV and V (Doster et al., 1982).

Sweet sorghum is similar to soybeans in that optimal planting occurs near the end of May. Hence, we would expect sorghum to be complementary with corn and competitive with soybeans during the planting periods. Sorghum has an apparent advantage over soybeans during the harvest periods because sorghum can be harvested earlier than corn or soybeans. This smoothing of the demand for machinery during harvest reduces the size of equipment needed and lowers the fixed machinery costs. On the other hand, soy-

TABLE IV

Average winter wheat yield (t/ha) for various planting and harvest dates in Central Indiana

Planting date	Harvest date									
	21 June— 27 June	28 June— 4 July	5 July— 11 July	12 July— 29 August						
27 September—										
10 October	4.170	4.102	4.035	3.901						
11 October—										
31 October	3.833	3.766	3.700	3.564						
1 November—										
21 November	a	3.430	3.363	3.228						

<sup>&</sup>lt;sup>a</sup> Winter wheat would not normally mature for harvest by the date shown.

TABLE V . Average double-crop soybean yields (t/ha) for various planting and harvest dates in Central Indiana

Planting date	Harvest date							
	11 October— 31 October	1 November— 21 November	22 November 5 December					
21 June-27 June	2.079	2.019	1.928					
28 June— 4 July	1.778	1.687	1.597					
5 July—11 July	a	1.386	1.296					

<sup>&</sup>lt;sup>a</sup> Double-crop soybeans would not normally mature for harvest by the date shown.

beans fix nitrogen into the soil. As a result, less nitrogen fertilizer has to be applied for subsequent crops. This gives an added economic incentive for growing soybeans in a yearly rotation with other crops (i.e. the two crops are grown alternately from year to year). This effect is modelled by considering crops grown with or without soybeans in rotation as two separate crops with appropriate profit and yield coefficients. Average yields of fermentable sugars from sorghum have been estimated for various planting and harvest periods in Indiana (Bender et al., 1983) and are shown in Table VI. These yield estimates are based on extrapolations from sweet sorghum literature and from field trials at West Lafayette, IN.

The model was run for a 300-ha farm, using central Indiana weather data and soil types (Parsons and Doster, 1980). The weather data were necessary to determine the number of days suitable for field work during each time period. The weather data were chosen to represent the 15th worst year out of 20. This is one way to incorporate the effect of resource uncertainty using a chance-constrained scheme (Charnes and Cooper, 1959). Twenty time periods were used to model the various activities. Typical machinery sets and working rates were used in the case study (Doster and McCarl, 1981). The input constraints are summarized in Table VII.

Four scenarios are reported in this case study. In the first, a low price (\$135/t) was assigned to sweet sorghum. All sweet sorghum prices are reported per ton of dry fermentable sugar. The fermentable sugars include non-structural carbohydrates from the sweet sorghum stalk and seed head. All of the other crops are reported on a total dry weight basis. The relatively low price of \$135/t was chosen so that only conventional crops would appear in the optimal crop budget. In the second scenario, a higher price (\$140/t) was assigned to sweet sorghum, and it began to enter the optimal solution as shown in Table VIII. As the sweet sorghum price was raised, sweet sorghum continued to replace corn in the optimal solution. Finally, at a price of \$150/t, sweet sorghum completely replaced corn as shown in Table VIII. This result is somewhat surprising since we would expect sweet

TABLE VI

Estimated yield of fermentable sugars from sweet sorghum (dry t/ha) for various plantings and harvest dates in Central Indiana

Planting date	Harvest date											
	12 July — 29 August	30 August — 12 September	13 September – 26 September	27 September — 10 October	11 October – 31 October							
3 May - 9 May	9.88	12.11	11.86	11.37	7.29							
10 May - 16 May	10.13	12.36	12.11	11.61	7.54							
17 May 23 May	9.88	12.36	12.11	11.74	7.66							
24 May - 30 May	a	11.49	11.98	11.86	7.41							
31 May - 6 June	a	9.27	11.61	11.74	7.04							
7 June - 13 June	a	5.31	10.01	10.75	6.42							
14 June – 20 June	a	$\mathbf{a}$	4.69	9.27	5.56							

<sup>&</sup>lt;sup>a</sup>Sweet sorghum would not normally mature for harvest by the dates shown.

TABLE VII

Constraints for sweet sorghum case study

Item (	Constraint or value used									
labor "		e, net pi	en at \$0 per ye cofit reflects re- labor.							
	Available in unlimited quantities at \$5/h with 80% efficiency.									
Custom work	None hir	ed-in or	hired-out							
prices	Soybean Wheat at	n at \$125.98/t bean at \$279.25/t eat at \$172.59/t prices are given on a dry weight basis)								
Variable costs	-	orn \$/ha)	Soybeans (\$/ha)	Wheat/double crop soybeans (\$/ha)	Sweet Sorghum (\$/ha)					
Fertilizer and lime		53.20	71.66	145.79	177.91					
Seed and chemicals		77.84	69.68	140.85	77.84					
Machine operation and dryi	_	24.29	70.05	133.67	824.47					
Interest and miscellaneous		40.77	28.04	43.24	40.77					
Field time	2	Good days based on 15th worst year in 20 in West Central Indiana; 6 days per working week; 10 h per working day.								
Machinery fixed costs		Based on 18% of list price								
Land charge			no land rental							
Drying rates		dequate								
Storage	A	.dequate	!							

TABLE VIII
Optimal Crop Mixes

	Scenario <sup>a</sup>	Land area					
		Sweet Sorghum	Corn	Soybeans	Wheat	Double crop soybean	Annual expected profit (\$)
1	Sorghum @ \$135/t	0	105.1	105.1	89.8	89.8	77885
2	Sorghum @ \$140/t	26.3	75.0	101.3	97.4	97.4	78864
3	Sorghum @ \$145/t	84.1	16.4	100.5	99.0	99.0	81217
1	Sorghum @ \$150/t	100.5	0	100.5	99.0	99.0	87063

<sup>&</sup>lt;sup>a</sup> Sweet sorghum prices are reported per ton of dry fermentable sugars.

sorghum to replace soybeans in the optimal crop budget (from the standpoint of competition for machinery during the planting and harvest periods shown in Table I). However, the added fertilizer benefits from growing crops in a yearly rotation with soybeans were enough to offset the competition for resources during the sorghum and soybean planting periods.

Some other interesting generalizations can be noted from this case study. In Scenario 1, the harvesting equipment shadow prices during time periods 17, 18 and 19 were \$104.07, \$39.71 and \$12.63, respectively. In other words, an additional hour of harvesting during time period 17 would improve the profits by \$104.07, etc. The reason for this constraining bottleneck is that corn and soybeans are both harvested during the same time periods with the same equipment, as depicted in Table I. Harvesting of these two crops is not completed until Period 20. In this solution, if one hour of harvesting were performed in an earlier period instead of in Period 20, returns would increase by the shadow price value.

In Scenario 3, the model selected corn and sweet sorghum to be grown in rotation with soybeans (i.e. 100.5 ha of each). In addition, 99.0 ha of land supported two crops, wheat and double-crop soybeans. This resulted in 399.0 ha of crops being harvested on 300 ha in 1 year. The demand for harvesting equipment was smoothed since sweet sorghum is harvested before corn or soybeans. With sweet sorghum in the optimal crop budget, the bottleneck during harvesting was eliminated (i.e. the shadow prices for harvest equipment were zero).

If all of the crops were compared on the basis of average return per ha, corn would appear to be the most profitable crop. However, when the various counter-intuitive production interactions and system dynamics are considered, a mixture of corn, soybeans, sweet sorghum, wheat and double-crop soybeans is optimal. This is advantageous from an integrated pest management standpoint because growing different crops decreases the probability of crop disease damage, insect damage and weed competition. In an actual setting the price relationships between the five crops would be expected to change until a new economic equilibrium point was achieved.

# DISCUSSION

The case study introduced an analysis procedure whereby energy crop feasibility can be more realistically assessed. Although a high fertility soil and central Indiana weather data were used, the model is general and can be used in other agricultural settings. We certainly are not recommending that producers immediately start to grow sweet sorghum. Sweet sorghum markets would need to develop and problems such as methods of storage, materials handling and processing are not solved. Sweet sorghum has demonstrated good potential as a feedstock for ethanol production. Research is continuing with this and other energy crops, and this work can help identify problem areas and opportunities.

The major limitation of this type of modelling is that solutions are based on long-run steady state behavior. As a result, the model does not explicitly consider variations in between-year linkages, such as field operations which may carry over from the fall to the spring. In addition, the model does not explicitly consider uncertainty in price and crop yields. Research is currently underway to incorporate a detailed agricultural production simulator with Model B-10 to overcome these limitations. This type of analysis would add insight concerning the day-by-day and year-round dynamics of crop production systems (Barrett and Peart, 1982).

# SUMMARY AND CONCLUSIONS

It is important to make early and continuing evaluations of energy crops to determine the regional production potentials and to show which direction crop breeding and management research should be directed. The analytical tool reported in this paper is a time-incorporated linear program called Purdue Crop Budget Model B-10. An example case study was run for a typical U.S. production system considering sweet sorghum as an energy crop.

The most profitable farm plans in the case study at the given prices were mixtures of corn, soybeans, wheat, double-crop soybeans and sweet sorghum. This was due to the extended planting and harvest periods and the lower machinery fixed costs which resulted from the smoother demand for field machinery. The results of this type of analysis can provide insight, beyond intuition, into the economic and technical feasibility of potential energy crops. This type of analysis will initially be valuable to agricultural researchers, and eventually will aid in the transfer of technology to production managers.

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